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Long distance real-time measurement of multi-points micro-vibration in region by digital holography

Lin Cong[a,*], Wen Xiao[a], Lu Rong[b], Feng Pan[a], Jianyi Li[a], Fanjing Wang[a], Zhaohai Zhang[a]

[a] School of Instrumentation Science and Opto-electronics Engineering, Beihang University, 37 Xueyuan Street, Haidian District, Beijing 100191, China
[b] Institute of Information Photonics Technology, College of Applied Science, Beijing University of Technology, 100 Pingleyuan Road, Beijing 100124, China

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ABSTRACT

Many applications require micro-vibration measurement, especially multi-points detection at long distance in real-time. In this paper, a micro-vibration measurement approach based on digital holographic interferometry is proposed for middle-low frequency detection. It can be used to monitor irregular frequency/amplitude vibration in selected region over 10 m away simultaneously and synchronously. A series of experiments were conducted including real-time measurement of 300 Hz, 1 kHz, 2 kHz and 3 kHz constant frequency/amplitude periodic vibration, precision and frequency response tests with calibration of LDV, 1 kHz irregular amplitude vibration, irregular frequency/amplitude vibration as well as the real-time measurement and simultaneous display of multi-points vibration. The experimental results demonstrate the feasibility of the proposed method and reveal its unique advantages.

1. Introduction

Great demand for micro-vibration (<3 kHz, λ/4–λ/100) measurement is required in many branches of engineering, i.e. aerospace [1], automotive [2], shipping [3] and MEMS (micro electro mechanical systems) [4]. The measurement approaches can be divided into point detection and area detection. The former category includes optical triangulation [5,6], moiré fringe [7], interference fringes [8,9], and laser Doppler vibration [10–15], assuming that any point in the detected area has the same vibration characteristics. While such assumption is not required for the latter category, i.e., holographic interferometry [16–22] and electronic speckle pattern interferometry (ESPI) [23–25]. Stetson and Powell demonstrated that for holographic recording architecture, interferograms indicating wave disturbances at different time can be generated for plane vibration measurement [16]. Khanna and Tonndorf proposed time-averaged holographic interferometry to detect absolute displacement amplitude at any point on the vibration plane through long time exposure [18]. However, this approach requires manual manipulation, and cannot investigate variant frequency vibration or real-time measurement. Santoyo developed ESPI, also known as TV holography, to visualize dynamic displacement of components from speckle patterns [23]. Doval et al. proposed double-exposure holographic interferometry which extracts instantaneous displacement by comparing two consecutive holograms [22]. Due to limited processing speed, these methods [16–23] have been just applied for ultra-low frequency (<100 Hz) vibration measurement while not yet being expanded to middle-low frequency spectrum. Pedrini et al. and Fu proposed high-speed digital holographic interferometry with high speed camera for vibration measurement up to 1 kHz [26–28]. But the detected distance is less than 2 m.

In this paper, we propose a real-time detection approach based on digital holographic interferometry for middle-low frequency micro-vibration measurement over 10 m. Vibration information is extracted directly and instantaneously from consecutive holograms using Fourier transform and filtering in frequency domain. Faster processing speed guarantees real-time vibration monitoring of selected area and dynamic measurement of irregular frequency/amplitude vibration. Using the high speed CMOS with smaller ROI (region of interest), the sampling rate of system is 48 kHz, and the highest detected vibration frequency is more than 2 kHz. Under the condition of long detected distance, a series of experiments have been conducted indicate: the detected range of frequency and precision of the proposed method.

2. Methods

There are three specific requirements for the algorithm of real-time vibration demodulation. (1) The algorithm should be simple for faster processing speed. (2) Due to the long detection distance, the algorithm should be independent on the spatial resolution. (3)

* Corresponding author.
E-mail address: conglin@aspe.buaa.edu.cn (L. Cong).

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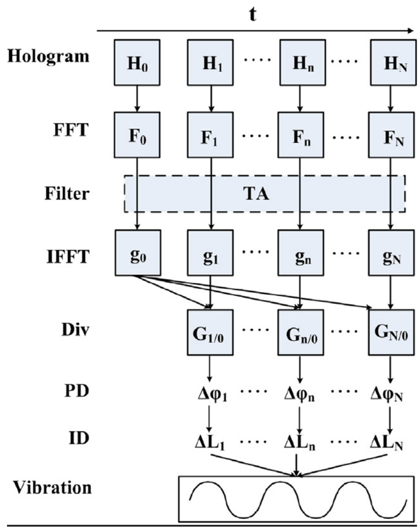

Fig. 1. Flow chart of the proposed method (FFT: fast Fourier transform, TA: filter task, IFFT: inverse Fast fourier transform, Div: divided, PD: phase demodulation, ID: instantaneous displacement).

For ease of use, it need not measure the power of object beam and reference beam before detection measurement. In this paper, we used a simplified vibration demodulation algorithm in which the vibration information is extracted from the holograms by transformation and filtering. The principle of the algorithm is illustrated in Fig. 1 and introduced below.

2.1. Recording digital holograms

The object beam $O(x, y, t) = O_0(x, y, t)e^{i\varphi_o(x,y,t)}$ interferences with the reference beam $R(x, y, t) = R_0(x, y, t)e^{i\varphi_r(x,y,t)}$ to form a hologram at the recording plane, in which $O_0(x, y, t)$ and $R_0(x, y, t)$ is the constant amplitude of the object beam and the reference beam, respectively. $\varphi_r = 2\pi(f_{0x}x + f_{0y}y)$ is the phase distribution of the reference beam, in which f_{0x} and f_{0y} are the carrier frequency at x and y direction. The hologram at the recording plane can be written as:

$$I(x, y, t) = \left|O(x, y, t) + R(x, y, t)\right|^2 = [O_0^2(x, y, t) + R_0^2(x, y, t)] + c(x, y, t)e^{-i\varphi_r(x,y,t)} + c^*(x, y, t)e^{i\varphi_r(x,y,t)}, \quad (1)$$

in which:

$$c = \frac{1}{2}[O_0(x, y, t)R_0(x, y, t)e^{i\varphi_o(x,y,t)}]$$

$$c^* = \frac{1}{2}[O_0(x, y, t)R_0(x, y, t)e^{-i\varphi_o(x,y,t)}].$$

2.2. Fast Fourier transform

Assuming that the initial recording time is t_0, a random recorded time during the vibration detection is t_n. The Fourier transform of the two corresponding holograms can be written as:

At t_0:

$$F_0(f_x, f_y) = \mathsf{F}[I_0(x, y)] = A(f_x, f_y) + C_0(f_x - f_{0x}, f_y - f_{0y}) + C_0^*(f_x + f_{0x}, f_y + f_{0y}). \quad (2)$$

At t_n:

$$F_n(f_x, f_y) = \mathsf{F}[I_n(x, y)] = A(f_x, f_y) + C_n(f_x - f_{0x}, f_y - f_{0y}) + C_n^*(f_x + f_{0x}, f_y + f_{0y}), \quad (3)$$

in which C_0 and C_n are the Fourier transform of virtual image c_0 and c_n, f_x and f_y are the coordinates at frequency domain.

2.3. Drawing filtering mask

In Eq. (1), $A = [O_0^2(x, y, t) + R_0^2(x, y, t)]$ is the zero-order image, $c(x, y, t)e^{-i\varphi_r(x,y,t)}$ is the virtual image and $c^*(x, y, t)e^{i\varphi_r(x,y,t)}$ is the real image. Before vibration, a filtering mask *TA* can be drawn based on the first hologram to extract C_0 and eliminate A and C^* in F_0 in the frequency domain. Assuming the optical setup and camera position do not change during the measurement, the same mask *TA* can be used to extract C_n in F_n. The inverse Fourier transform of C_0 and C_n are expressed as:

$$g_0(x, y) = \mathsf{F}^{-1}[C_0(f_x - f_{0x}, f_y - f_{0y})] = c_0(x, y)e^{i2\pi(f_{0x}x + f_{0y}y)} = \frac{1}{2}O_0(x, y)R_0(x, y)e^{i\varphi_{o0}(x,y)}e^{i2\pi(f_{0x}x + f_{0y}y)}. \quad (4)$$

$$g_n(x, y) = \mathsf{F}^{-1}[C_n(f_x - f_{0x}, f_y - f_{0y})] = \frac{1}{2}O_0(x, y)R_0(x, y)e^{i\varphi_{on}(x,y)}e^{i2\pi(f_{0x}x + f_{0y}y)}. \quad (5)$$

2.4. Calculating phase change

The phase change $\Delta\varphi_o$ due to vibration can be extracted by filtering $O_0(x, y, t)$ and $R_0(x, y, t)$ using Euler's formula:

$$G(x, y) = \frac{g_n(x, y)}{g_0(x, y)} = e^{i[\varphi_{on}(x,y) - \varphi_{o0}(x,y)]} = e^{i\Delta\varphi_o(x,y)} = \cos[\Delta\varphi_o(x, y)] + i\sin[\Delta\varphi_o(x, y)], \quad (6)$$

$$\Delta\varphi_o(x, y) = \arctan\left\{\frac{Im[G(x, y)]}{Re[G(x, y)]}\right\}. \quad (7)$$

2.5. Demodulation of instantaneous vibration displacement (IVD)

If the vibration amplitude object is less than wavelength, i.e., $\Delta\varphi_o(x, y) \in [-\pi, \pi]$, IVD is

$$\Delta L(x, y) = \frac{\lambda}{4\pi}\Delta\varphi_o(x, y). \quad (8)$$

2.6. Draw vibration curve

Selecting a random pixel in the measured region, the corresponding IVD can be calculated and output as a real-time vibration curve. It is noted that vibration information of any point within that region is restored in holograms, thus this approach is applicable for plane vibration detection.

3. Experiments and results

3.1. Experimental system

The experimental setup, as depicted in Fig. 2, was based on a modified Michelson interferometer configuration. A doubled-frequency Nd:YAG laser with a power of 50 mW and a wavelength of 532 nm was used as a light source. A polarized beam splitter (PBS) was adopted to split and adjust the intensity ratio of the illumination beam to reference beam with the help of two attenuators (A1 and A2). Two half wave plates (HWP1 and HWP2) were used to obtain the same linear polarization state of the two beams, which were collimated as plane waves by beam expanders (BE1 and BE2